I. Physics of pair producing gaps in black hole magnetospheres

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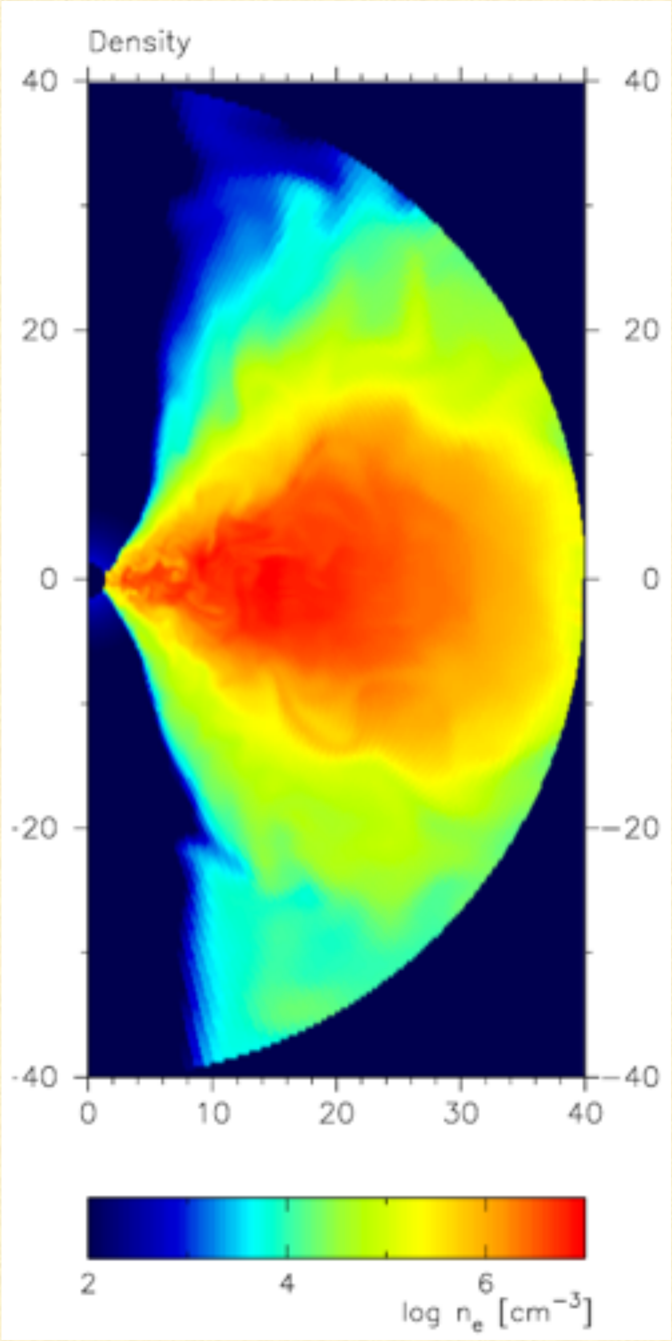
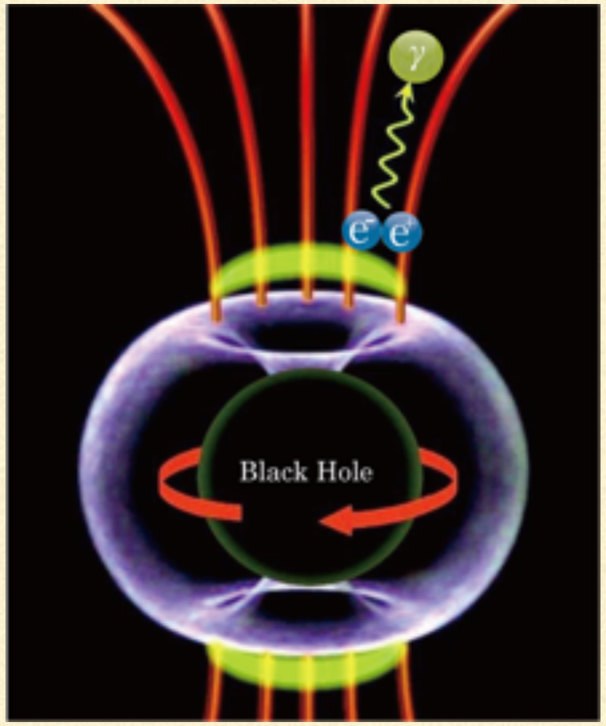
Physics of the gap

- In black hole jets, the plasma supply in the funnel region has been a long standing problem.
- Centrifugal barrier prevents accretion material to penetrate into the jet. But plasma is required to conduct the BZ current.

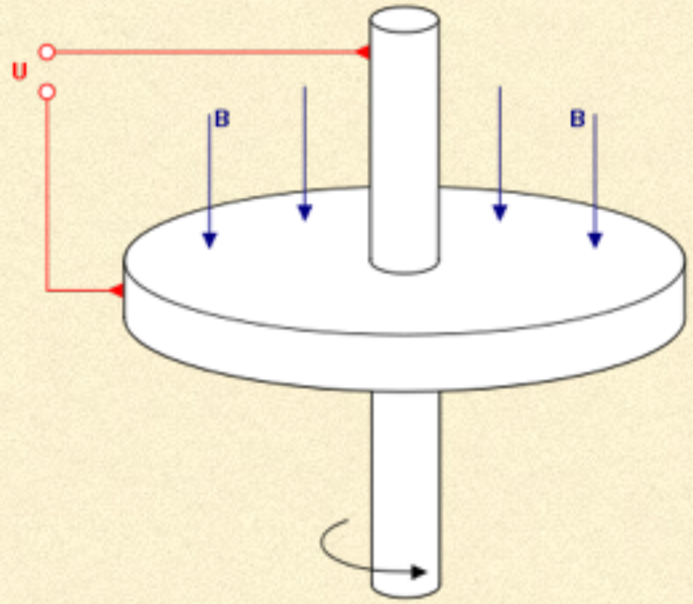


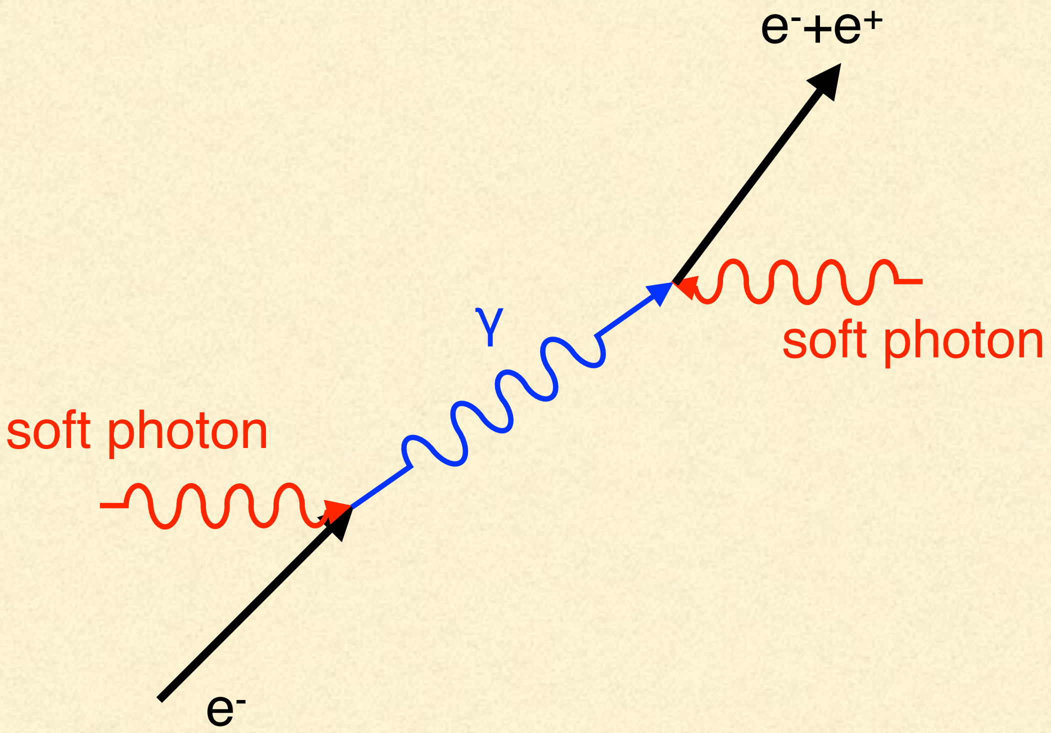
Mościbrodzka et al 2011

Physics of the gap



MAGIC collaboration



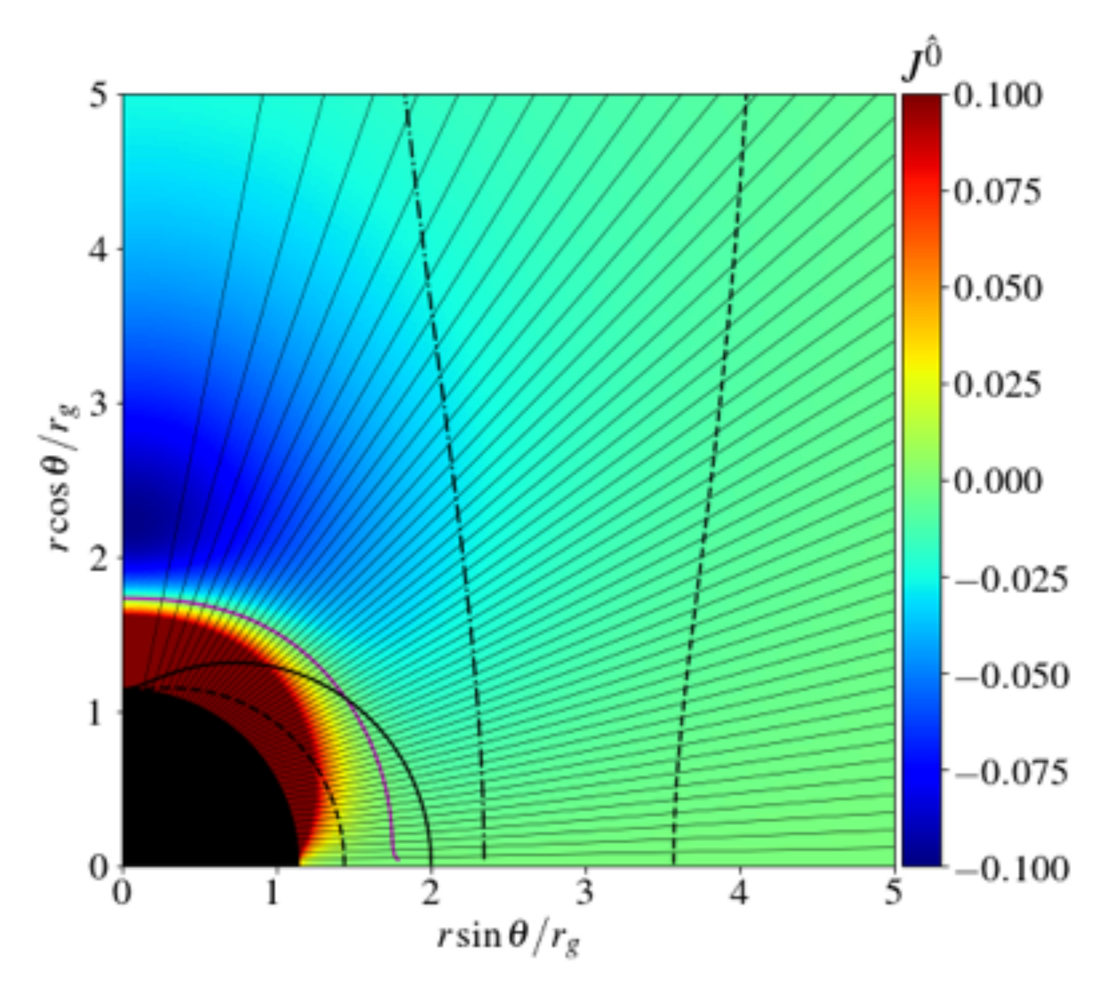


- Where does pair creation happen? What is the dynamics of the gap?
- How much energy is dissipated in the gap?

cf. Beskin et al. 1992; Hirotani & Okamoto 1998; Broderick & Tchekhovskoy 2015; Hirotani & Pu 2016; Levinson & Segev 2017; Levinson & Cerutti 2018; Parfrey et al 2019; etc.

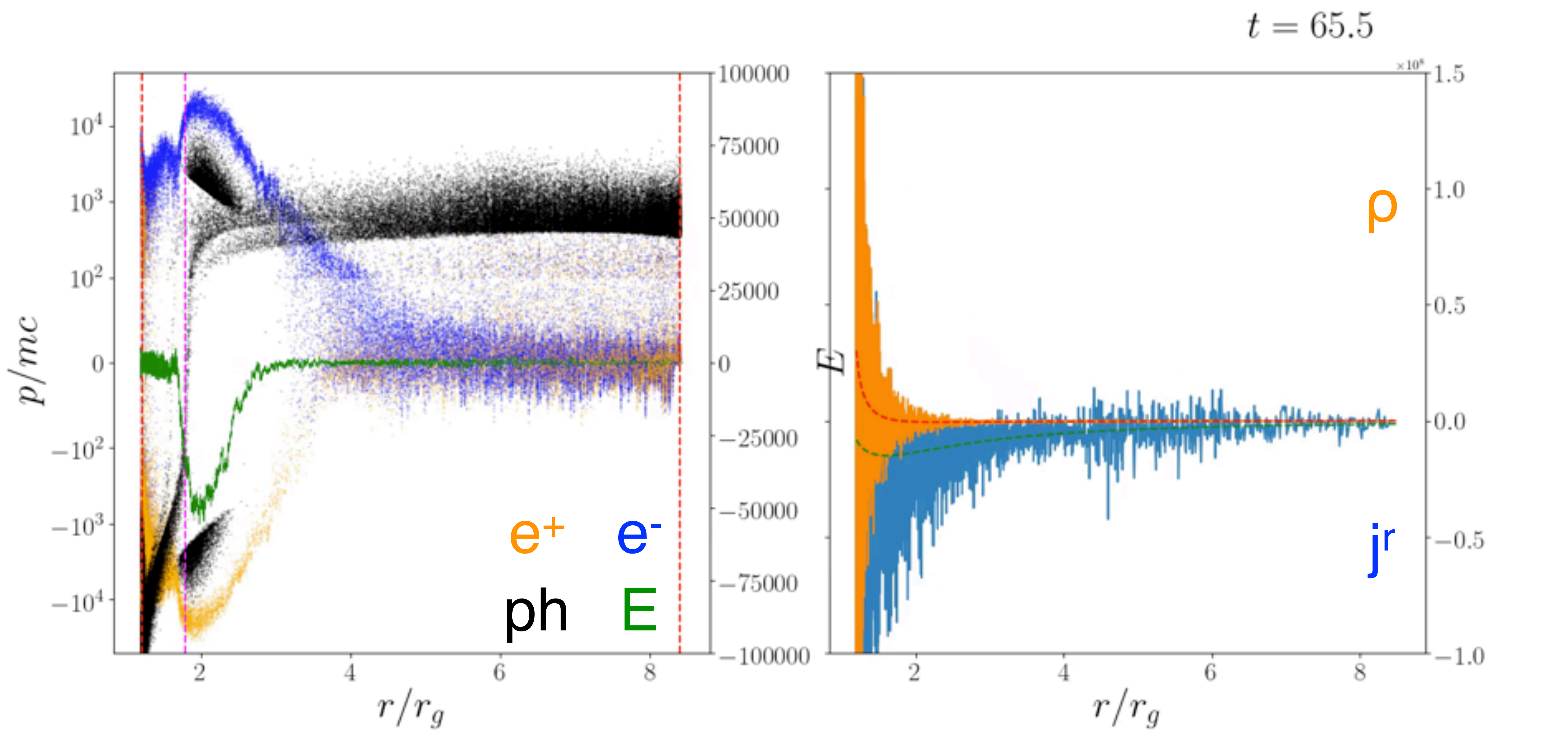
Full GR 1D PIC simulations

- 1D dynamics in full GR along a flux tube taken from global GR force-free solutions
- Particle motion confined to field lines, like bead on a wire
- Electrostatic gap develops when charge/current density deviates from background (force-free) values
- Fully self-consistent IC scattering and γγ pair production processes
- GPU GRPIC code *Aperture* developed by Alex Chen



cf. Chen, Yuan & Yang 2018

Full GR 1D PIC simulations



Highly time dependent, quasi-periodic gap dynamics!

Chen & Yuan, in preparation

II. Formation of lamp-post coronae in Seyfert Galaxies

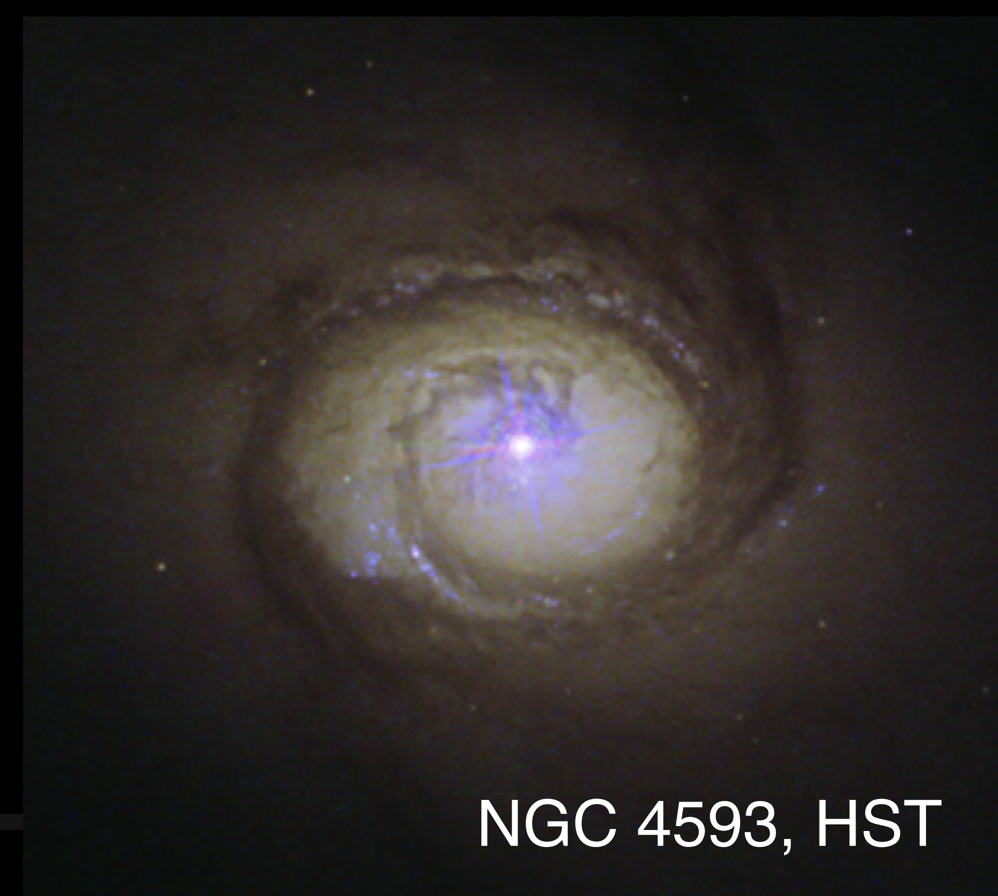
Yajie Yuan (Spitzer Fellow, Princeton)

In collaboration with: Roger Blandford, Dan Wilkins (Stanford) and Anatoly Spitkovsky, Alex Chen (Princeton)

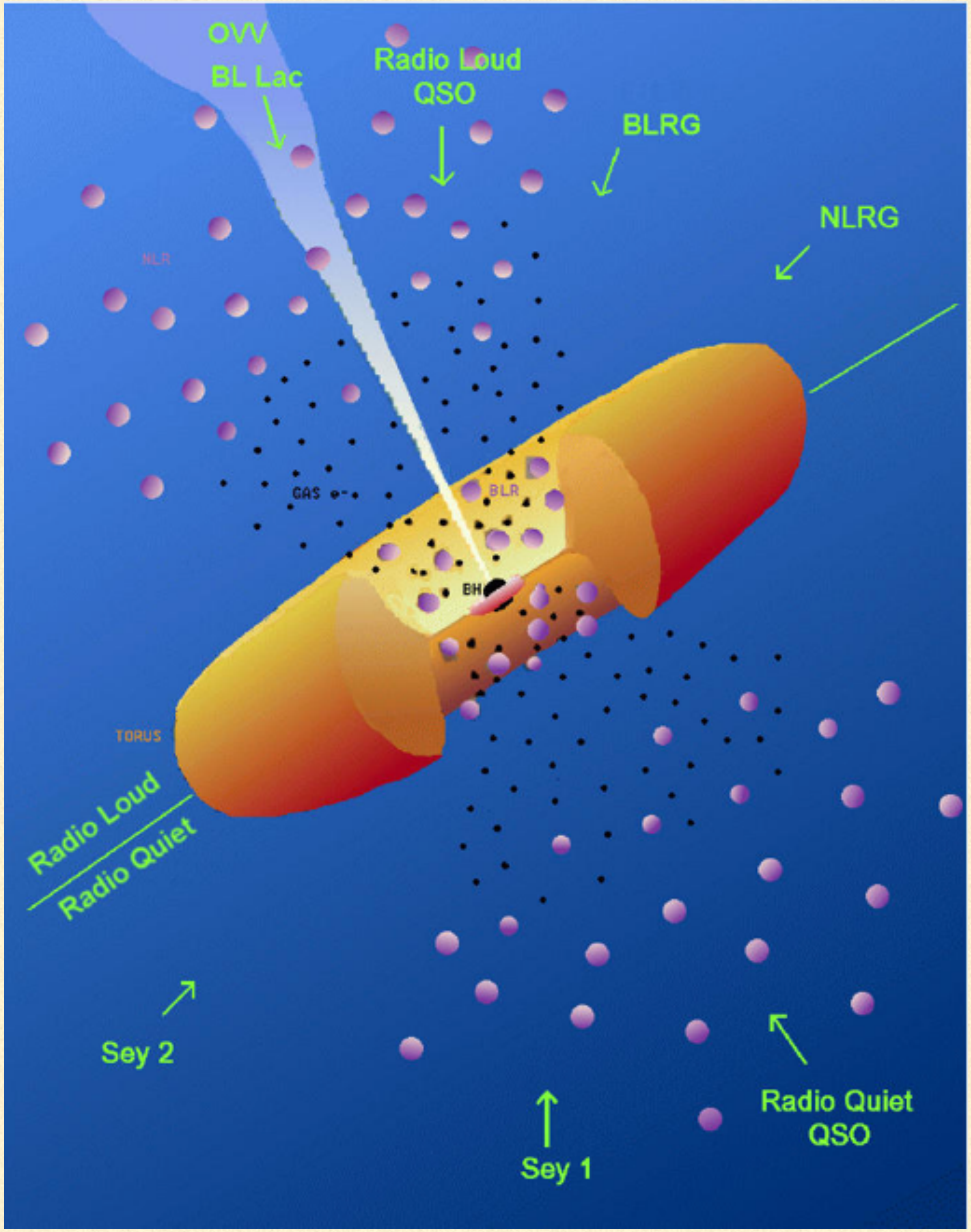
NGC 4151, HST

NGC 4051, Liverpool Telescope

NGC 5548, HST



NGC 4593, HST

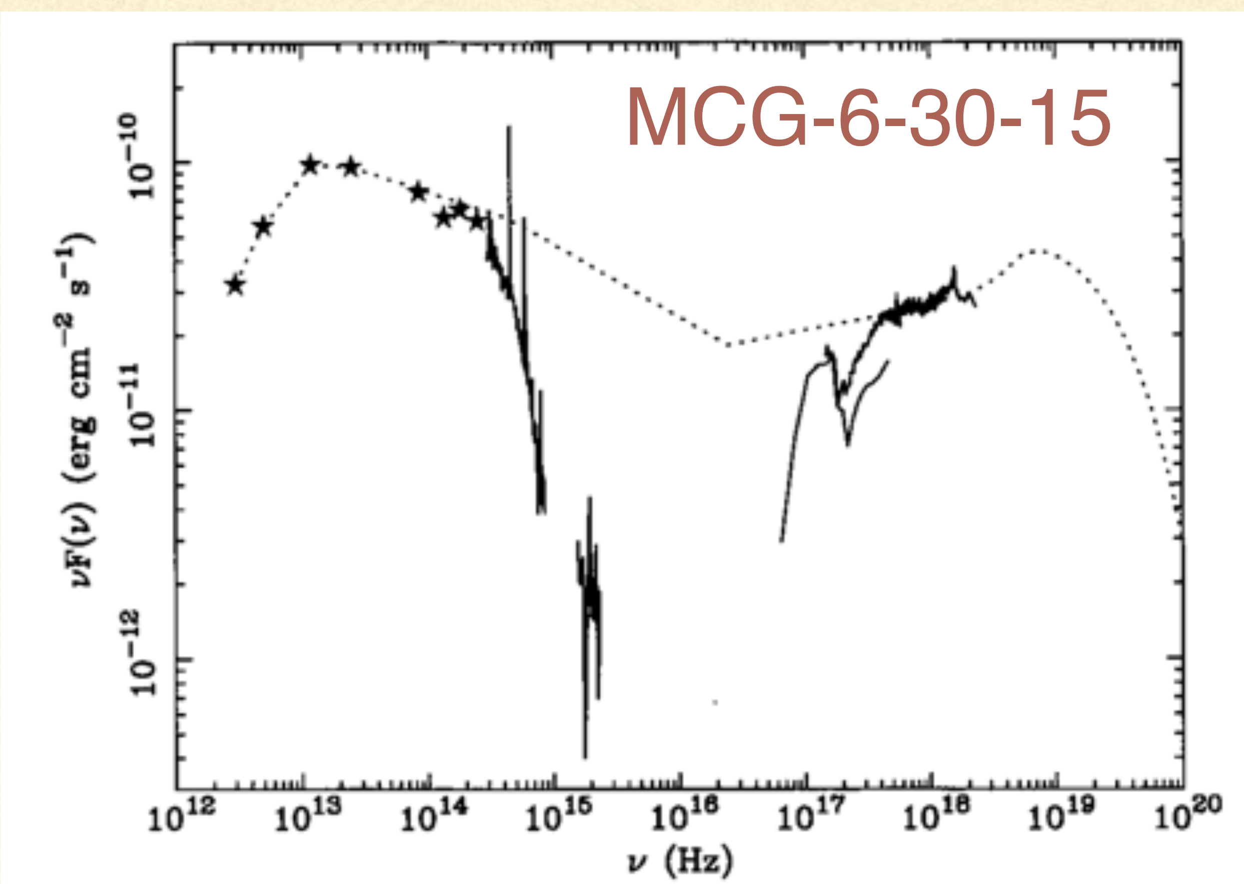


Urry & Padovani

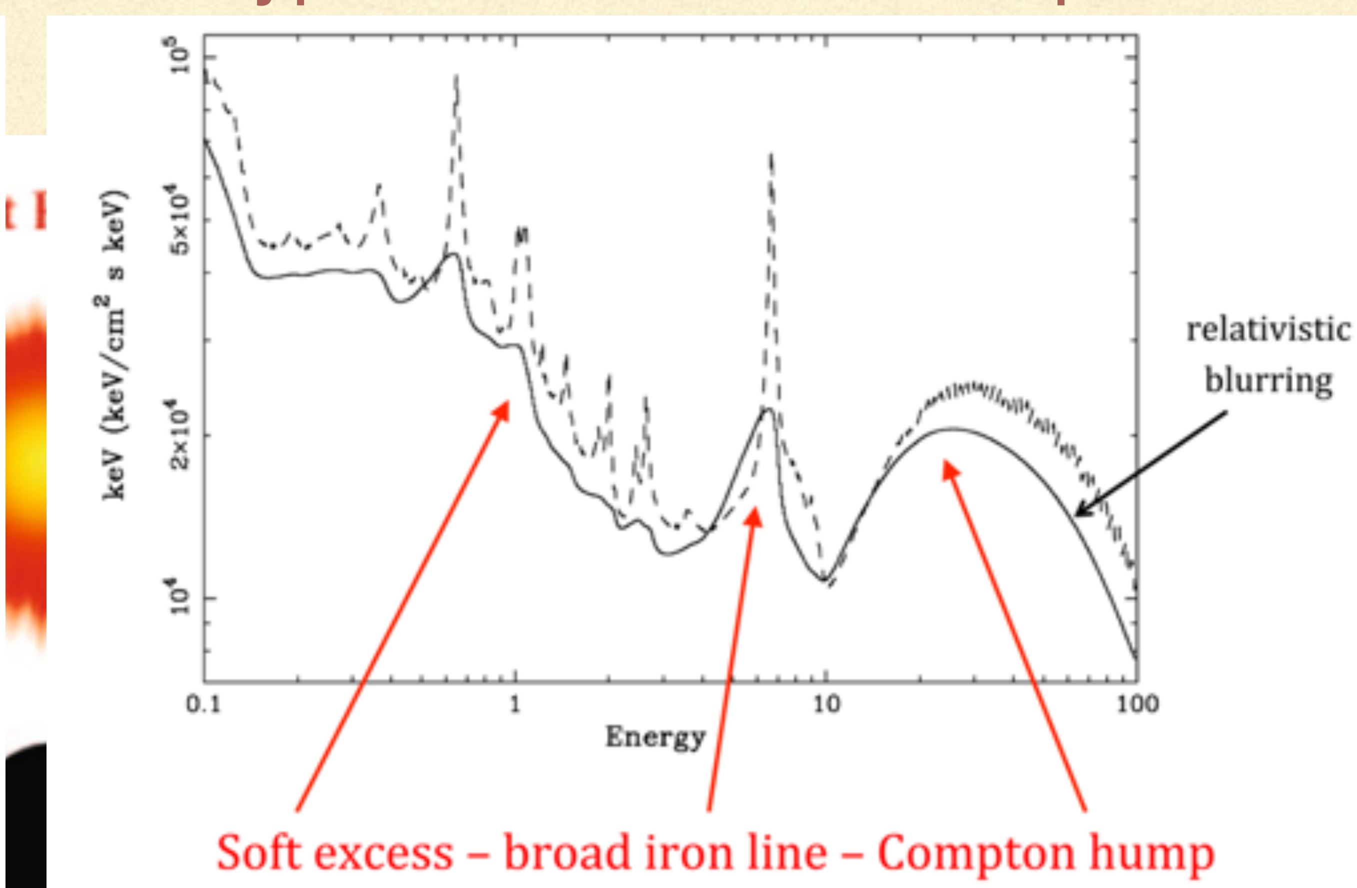
X-ray coronae in Seyfert Galaxies

- Spiral galaxies, $M \sim 10^6$–$10^8\ M_\odot$, Radio quiet
- $L \sim 0.01 - 1\ L_{Edd}$
- $L_X \sim L_{O/UV}$

typical local reflection spectrum



Reynolds+1997



Uttley+2014

Lamppost coronae?

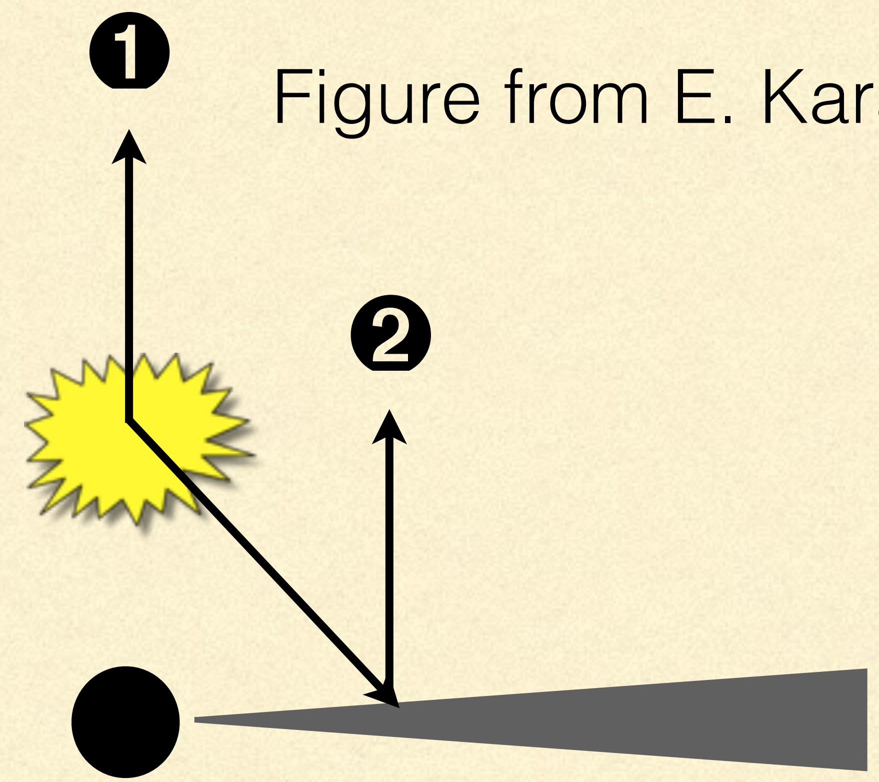
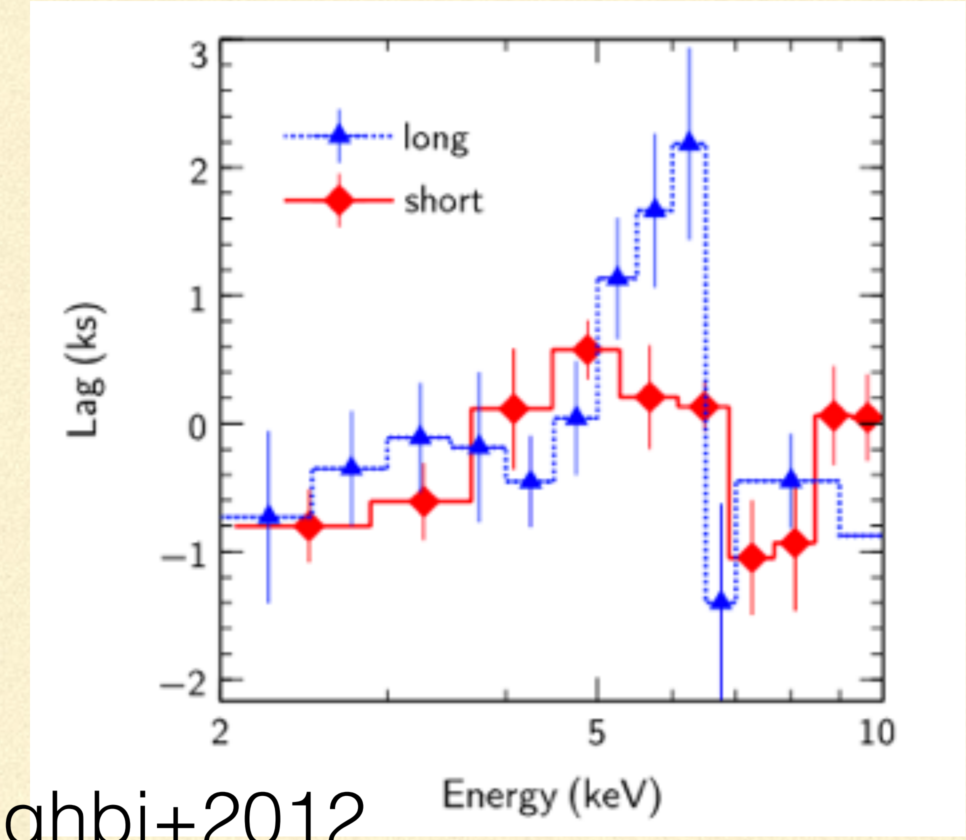


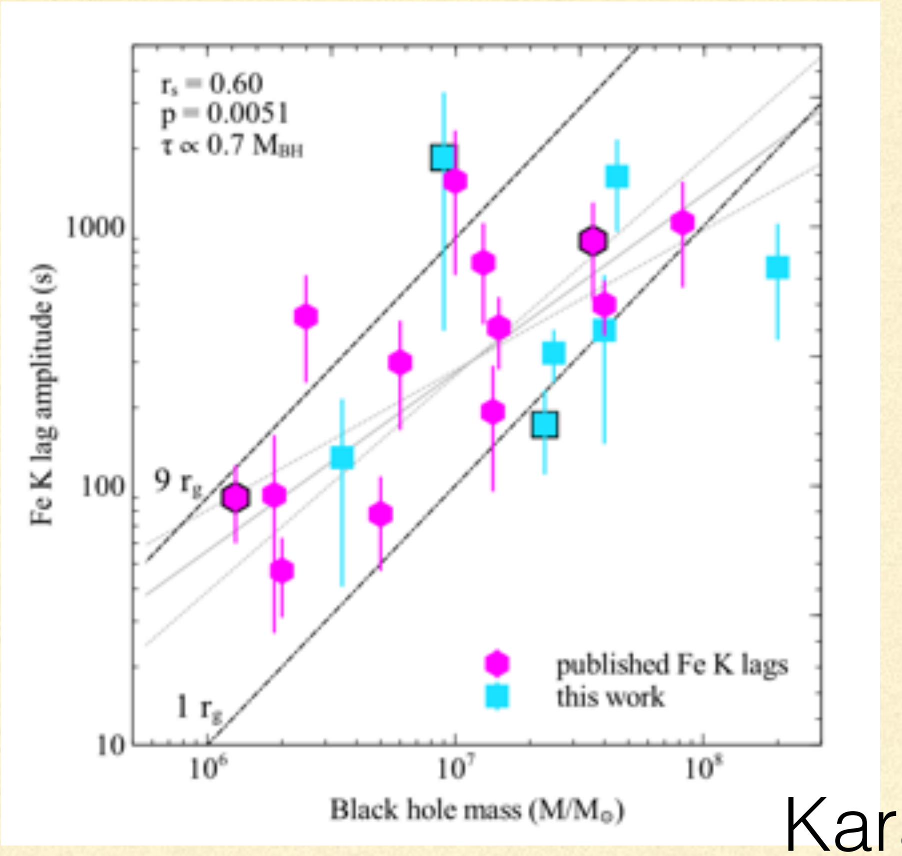
Figure from E. Kara

- Reverberation mapping
- Emissivity profile modeling
- Microlensing

Iron K lag in NGC 4151



Zoghbi+2012

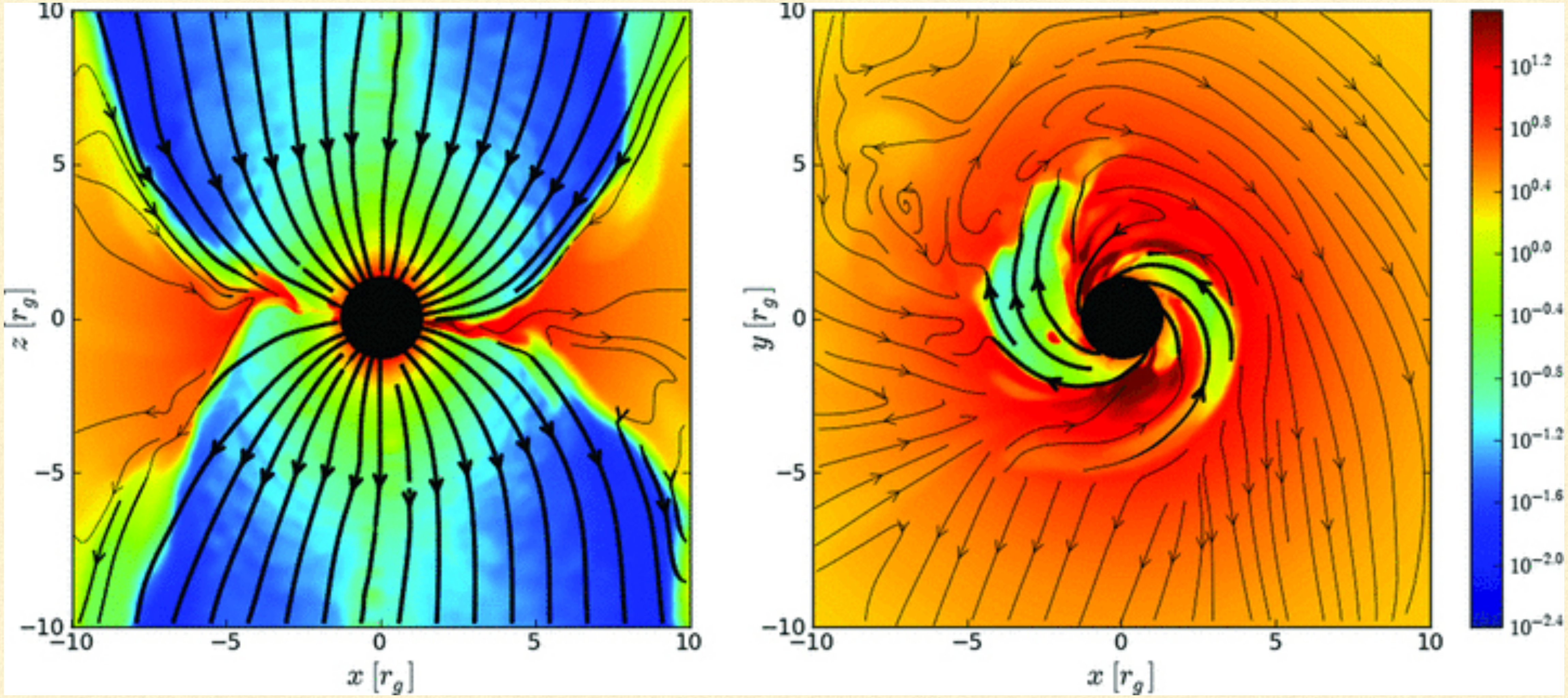


Kara+2016

Questions to answer

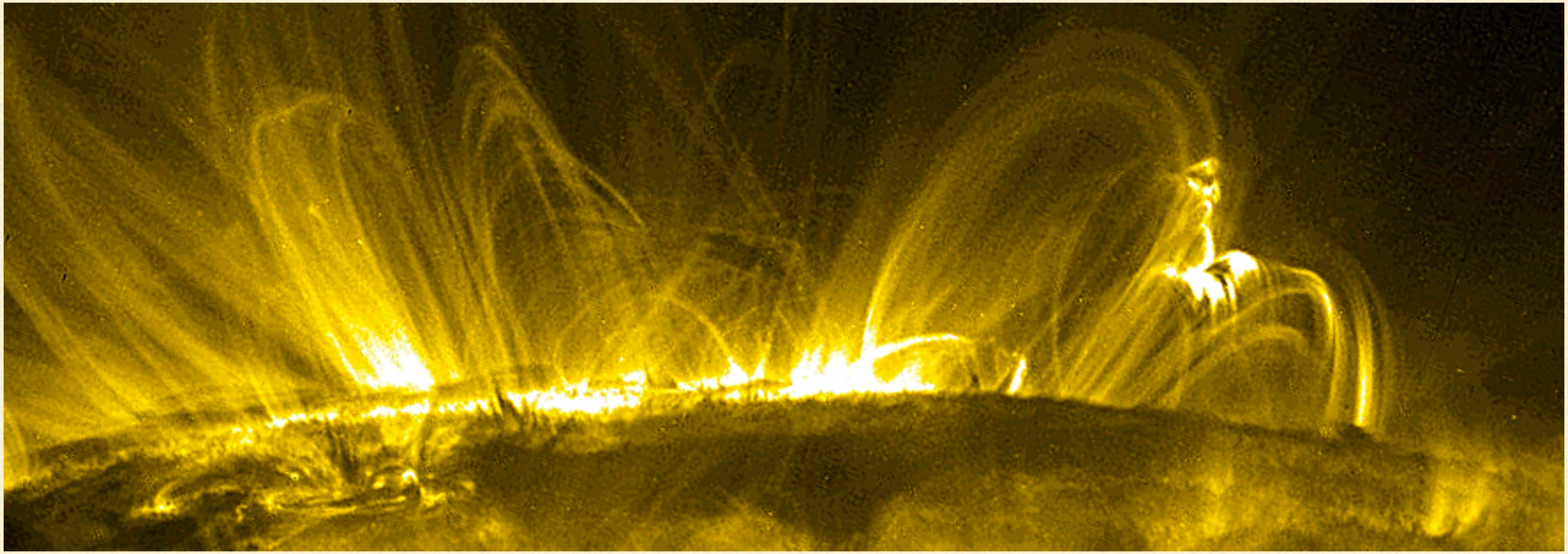
- Why is the corona so compact, and located at such a special place (a few gravitational radii above the BH)?
- Why is the X-ray luminosity so high?
- Is this relevant to the radio loud/quiet dichotomy?

On jet formation…



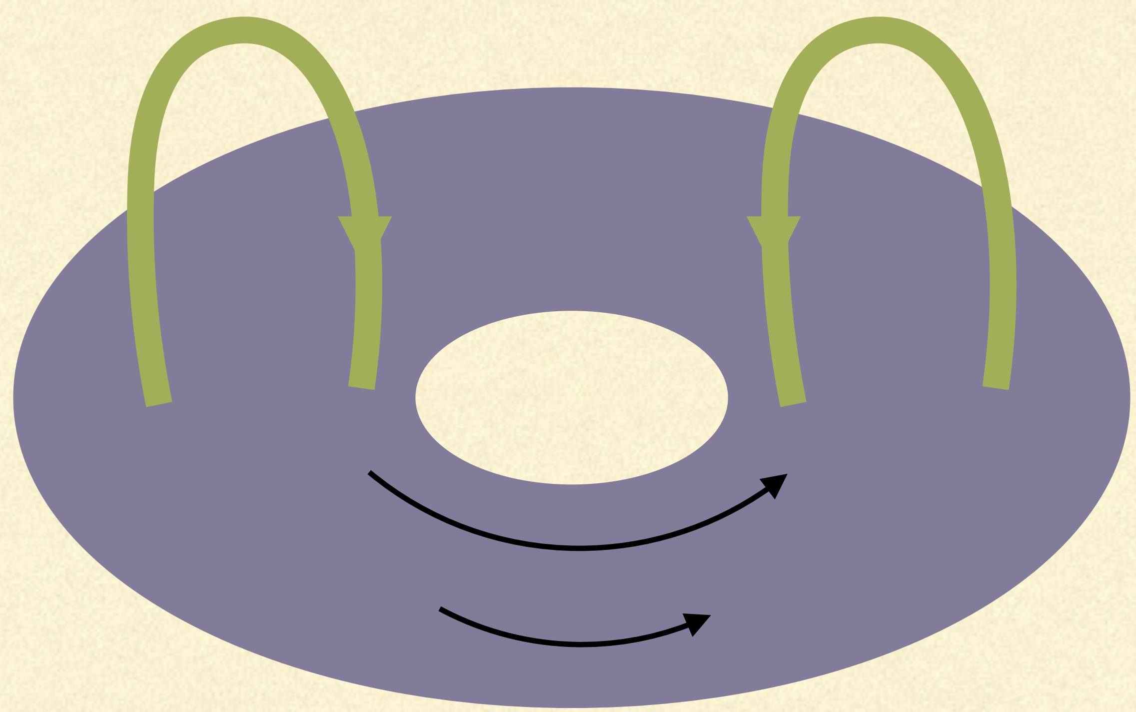
McKinney et al 2012

Solar corona analogy?



Magnetic “carpet” above the disk: e.g., Uzdensky & Goodman 2008

A Possible scenario:
tangling of small scale flux tubes near the axis



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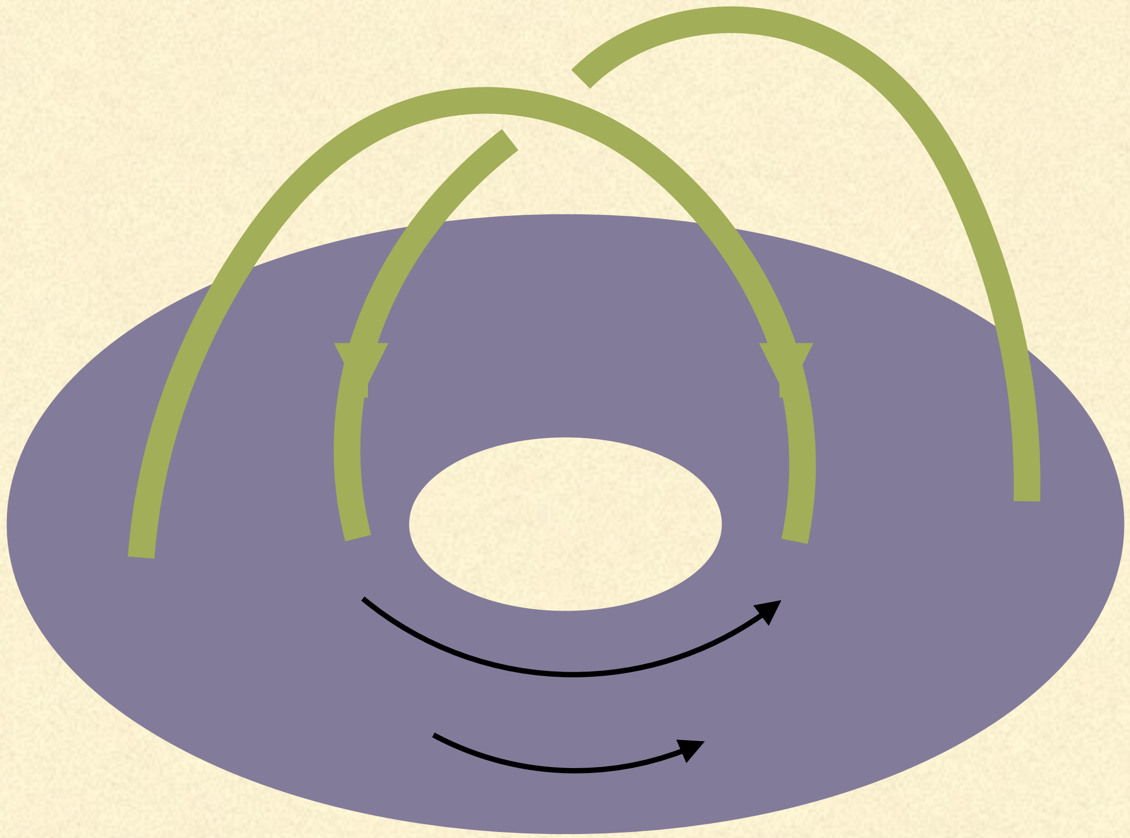

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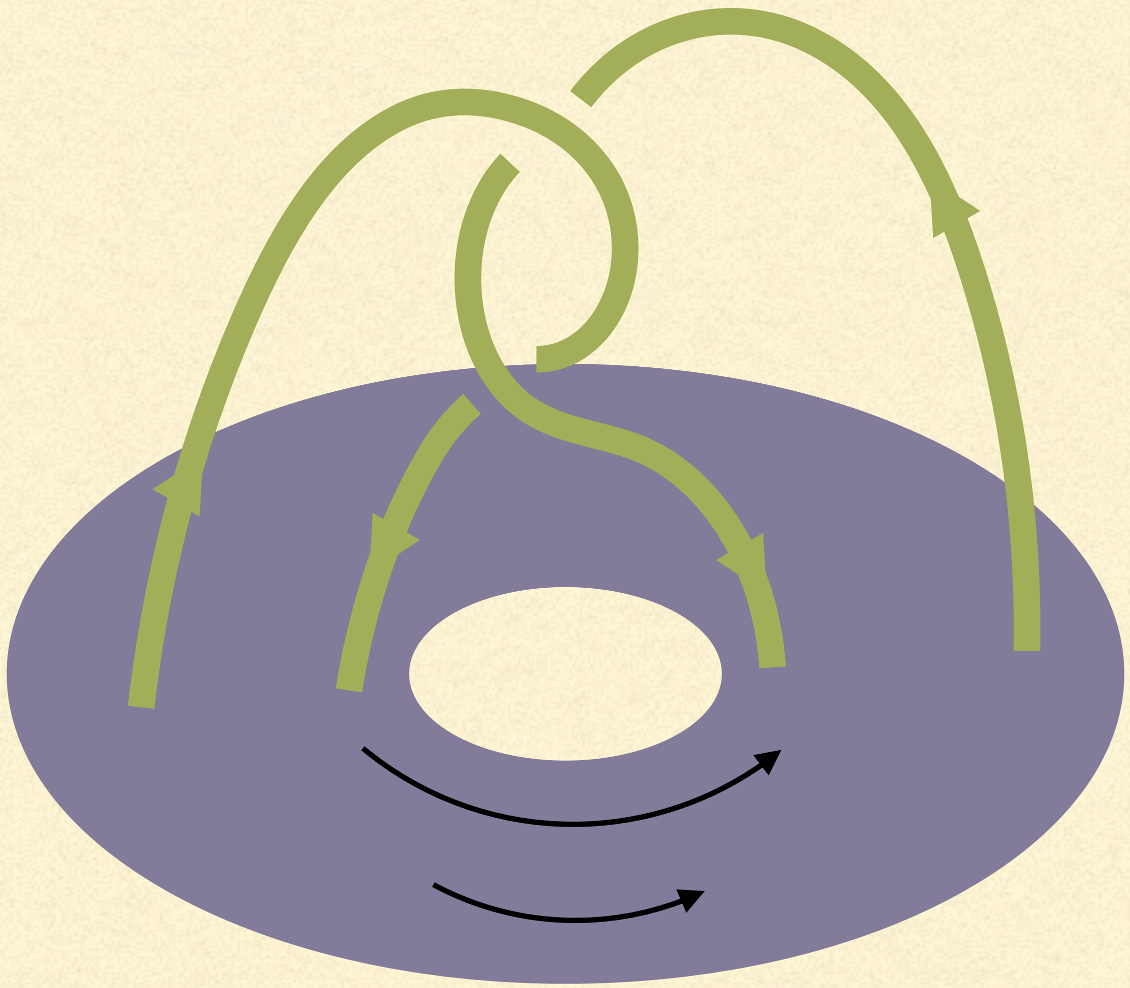

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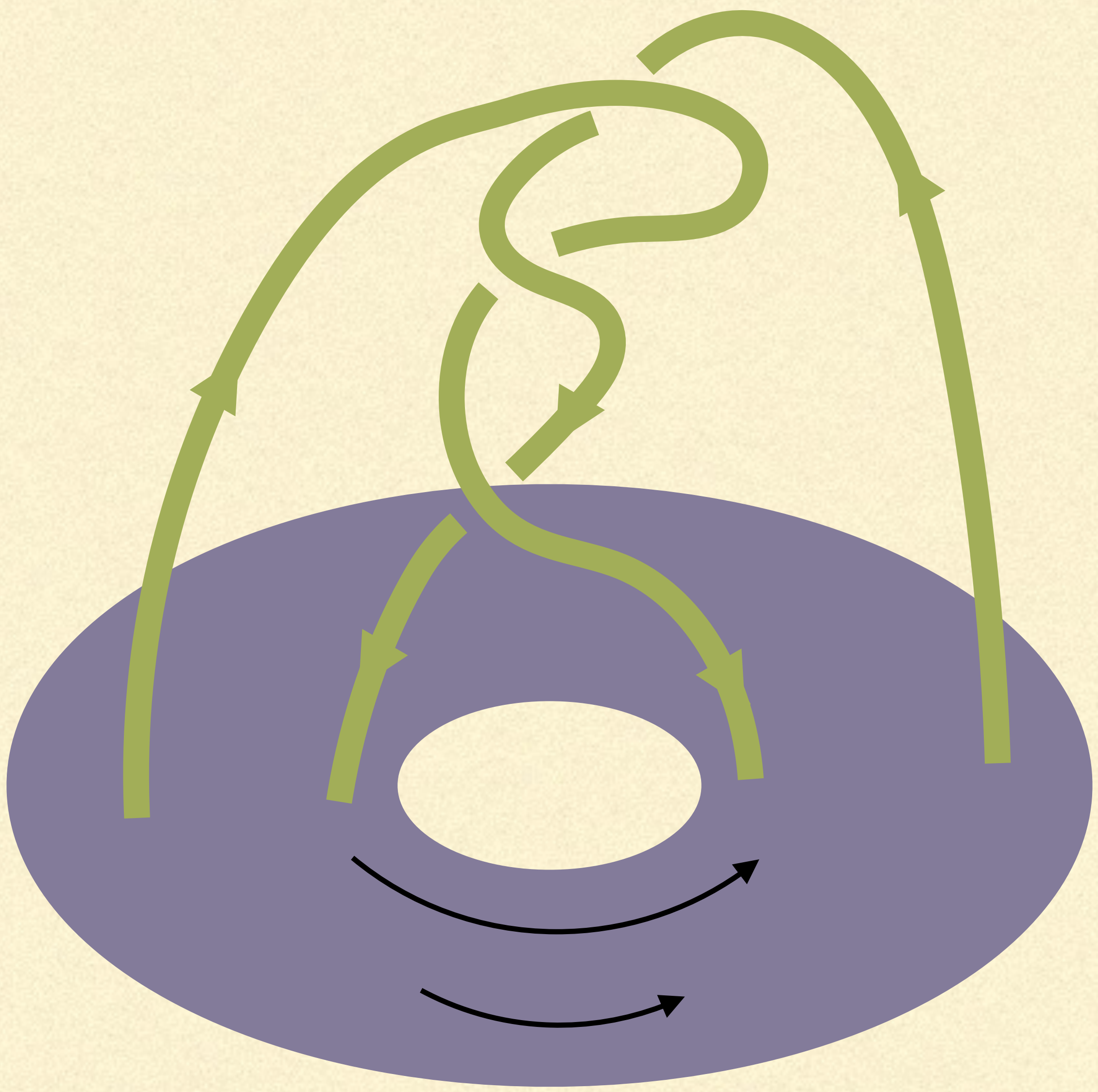


A simple toy model

Force-free electrodynamics:

$$\rho\mathbf{E} + \mathbf{j} \times \mathbf{B} = 0$$

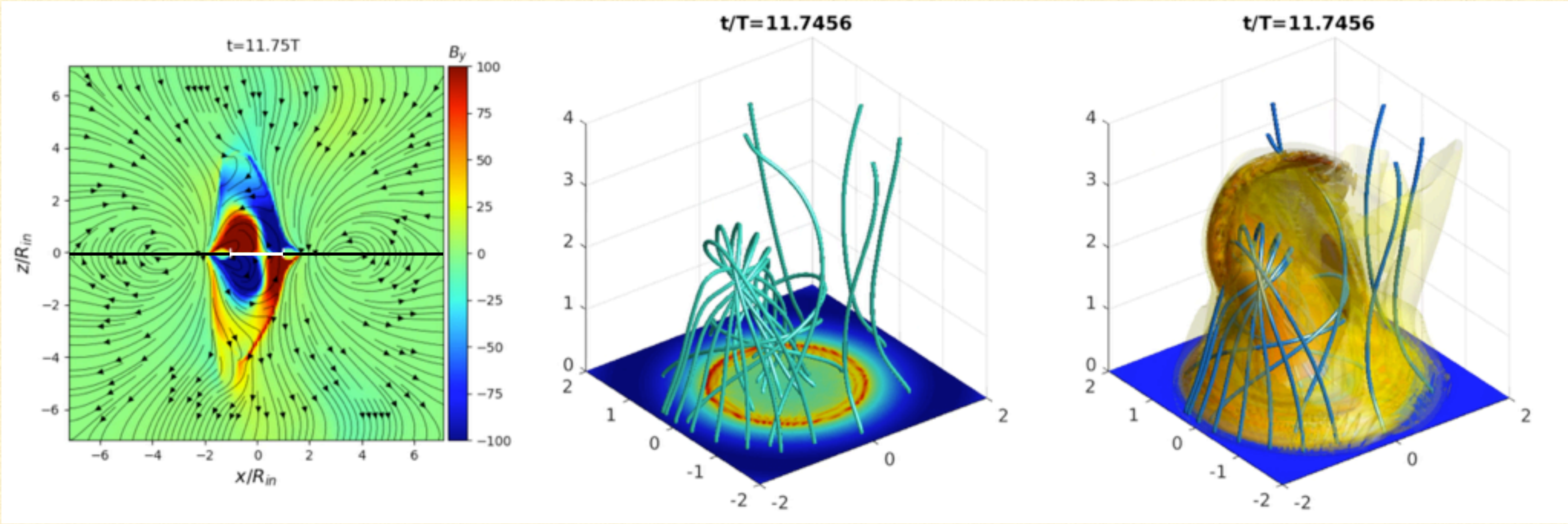
Neglect plasma inertia and thermal effects (good approximation outside the disk)

Magnetic stress pushes/pulls the field around!

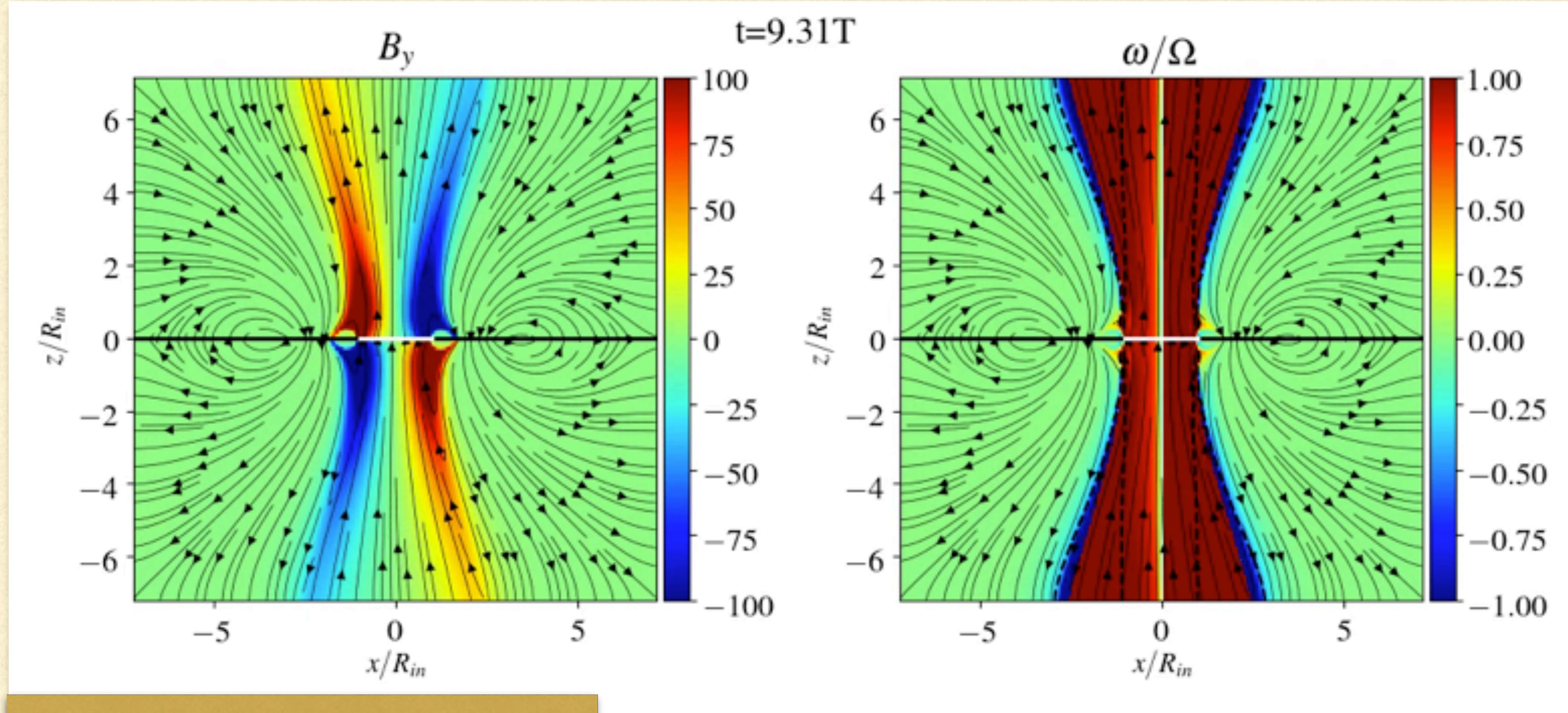
A simple toy model

- We use the time-dependent, relativistic force-free code originally developed by Anatoly Spitkovsky (2006)
- Setup: a central compact object is rotating and twisting up the field, while the accretion disk is non-rotating

(cf. Parfrey et al 2015, axisymmetric GRFFE simulations)

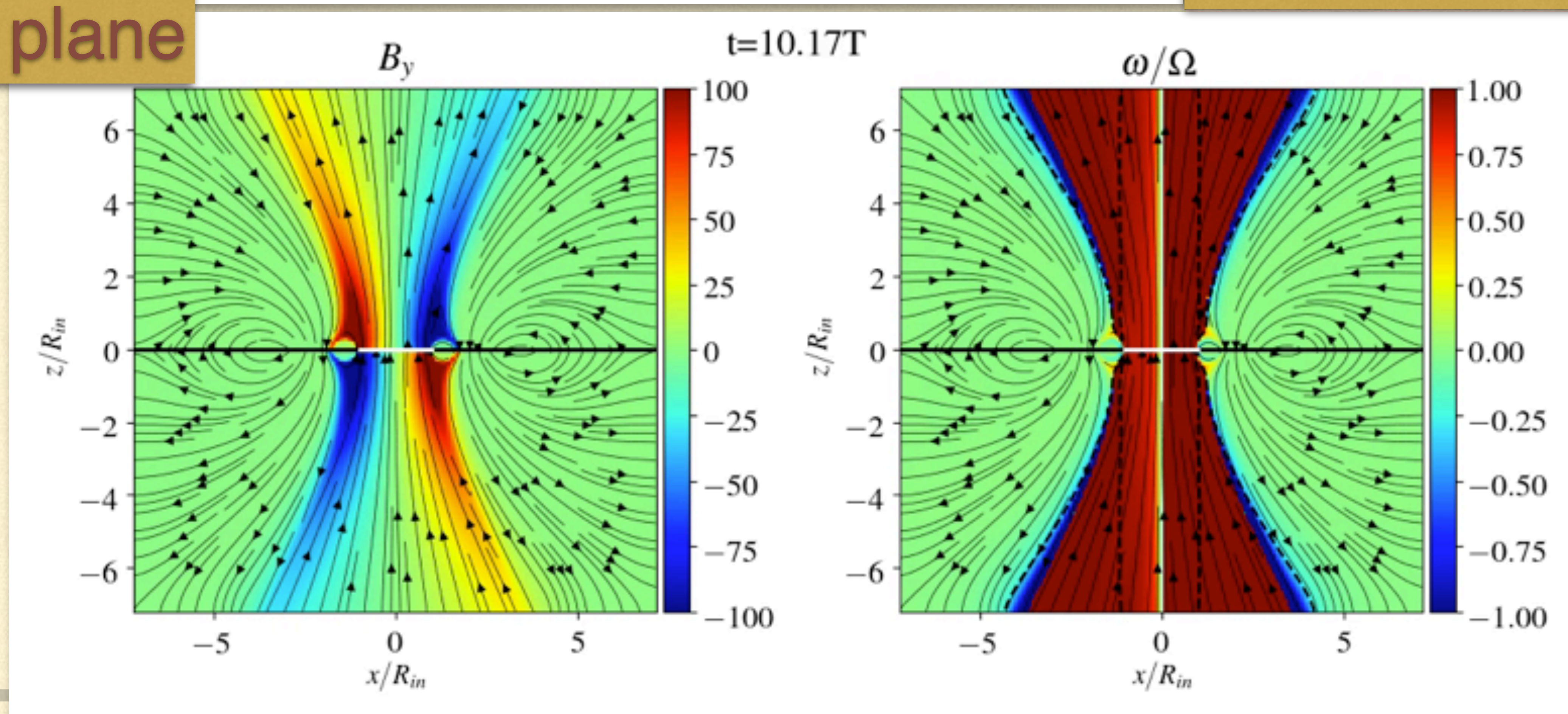


Yuan et al, arXiv1901.02834



Angular velocity of field lines

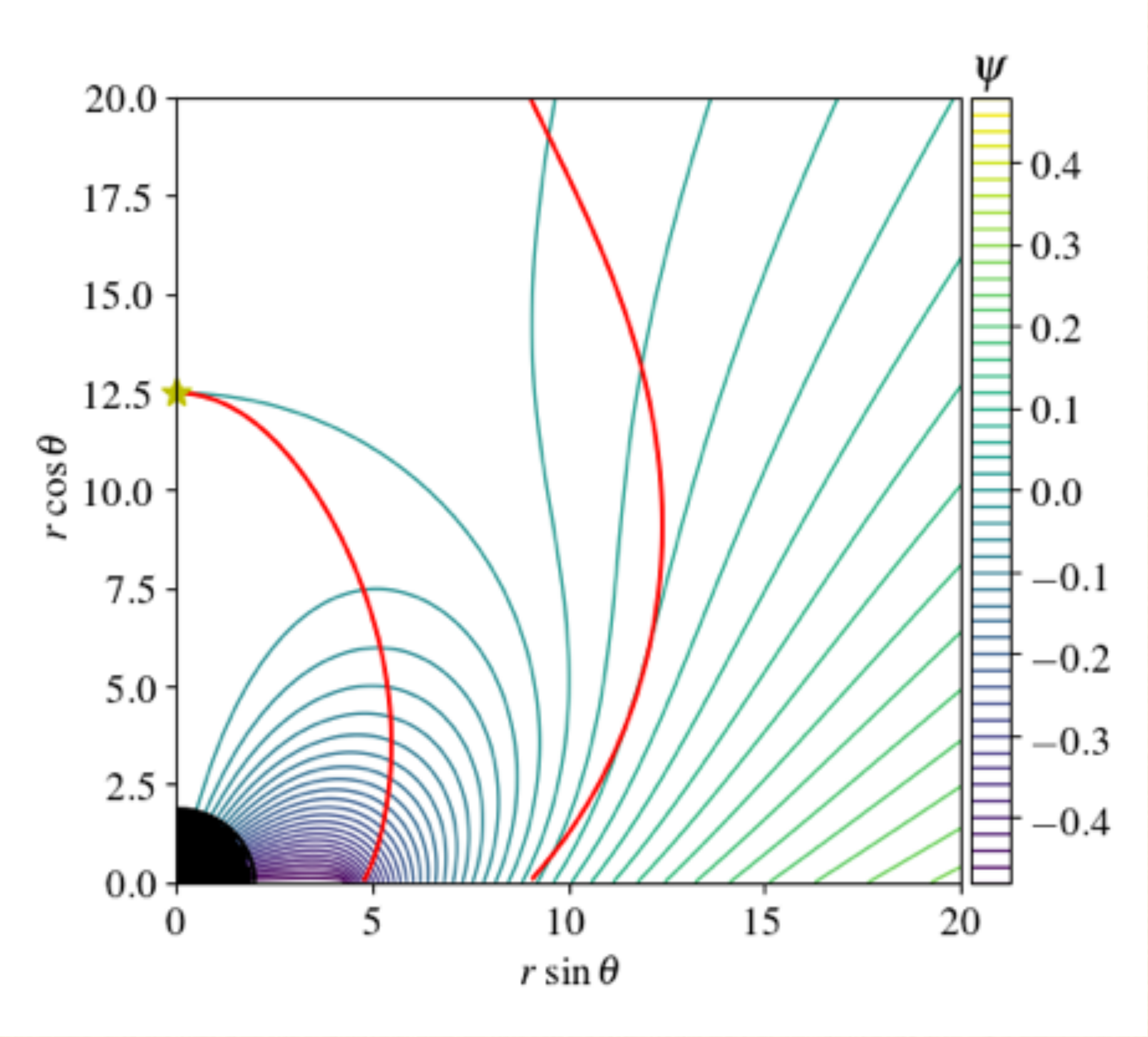
Field on x-z plane



A black hole twisting up the field

Black hole is like a resistive sphere!

What's the extent of the closed zone?

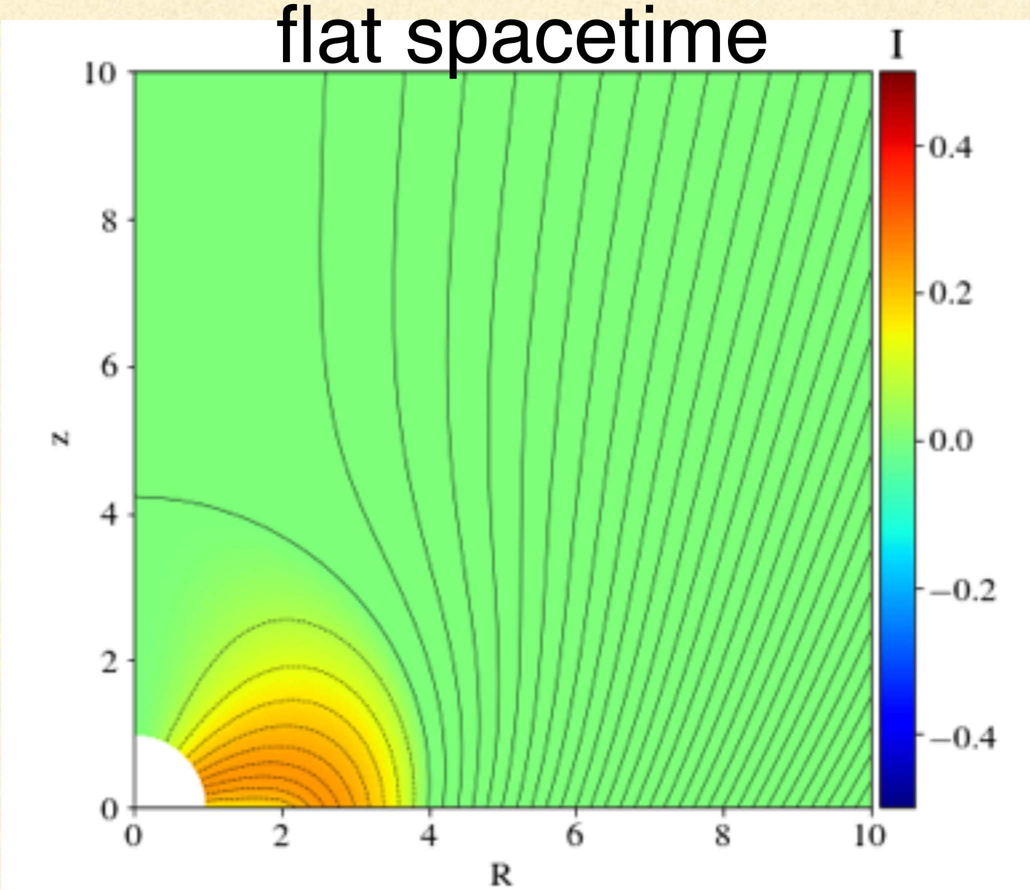


Yuan, Blandford & Wilkins 2018
Previous study: Uzdensky 2004, 2005

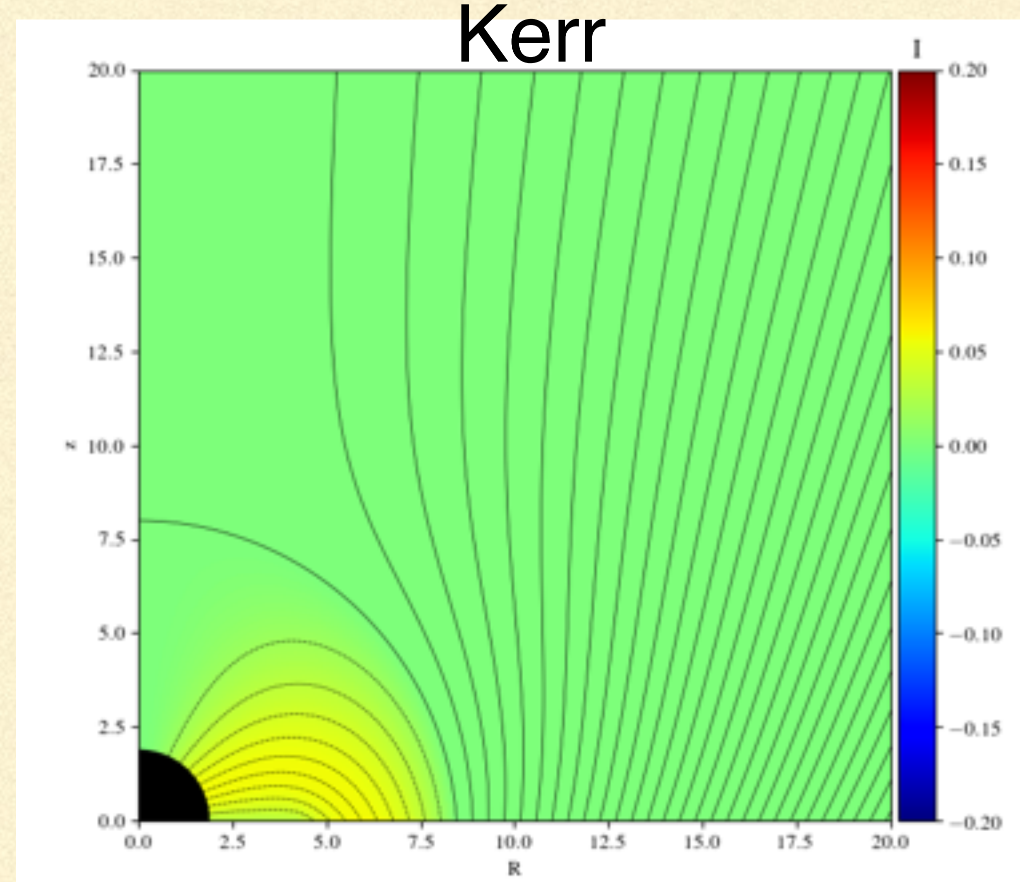
Time dependent simulation—a test case

- We use the time-dependent, relativistic force-free code originally developed by Anatoly Spitkovsky (2006)
- Mimicking the electromagnetic effect of the black hole using a rotating, resistive membrane in flat spacetime
  - On the membrane, in corotating frame, $B_{||}'=4\pi K$, $E_{||}'=RK=4\pi K=B_{||}'$, where K is the surface current, R=4π is the surface resistivity

flat spacetime

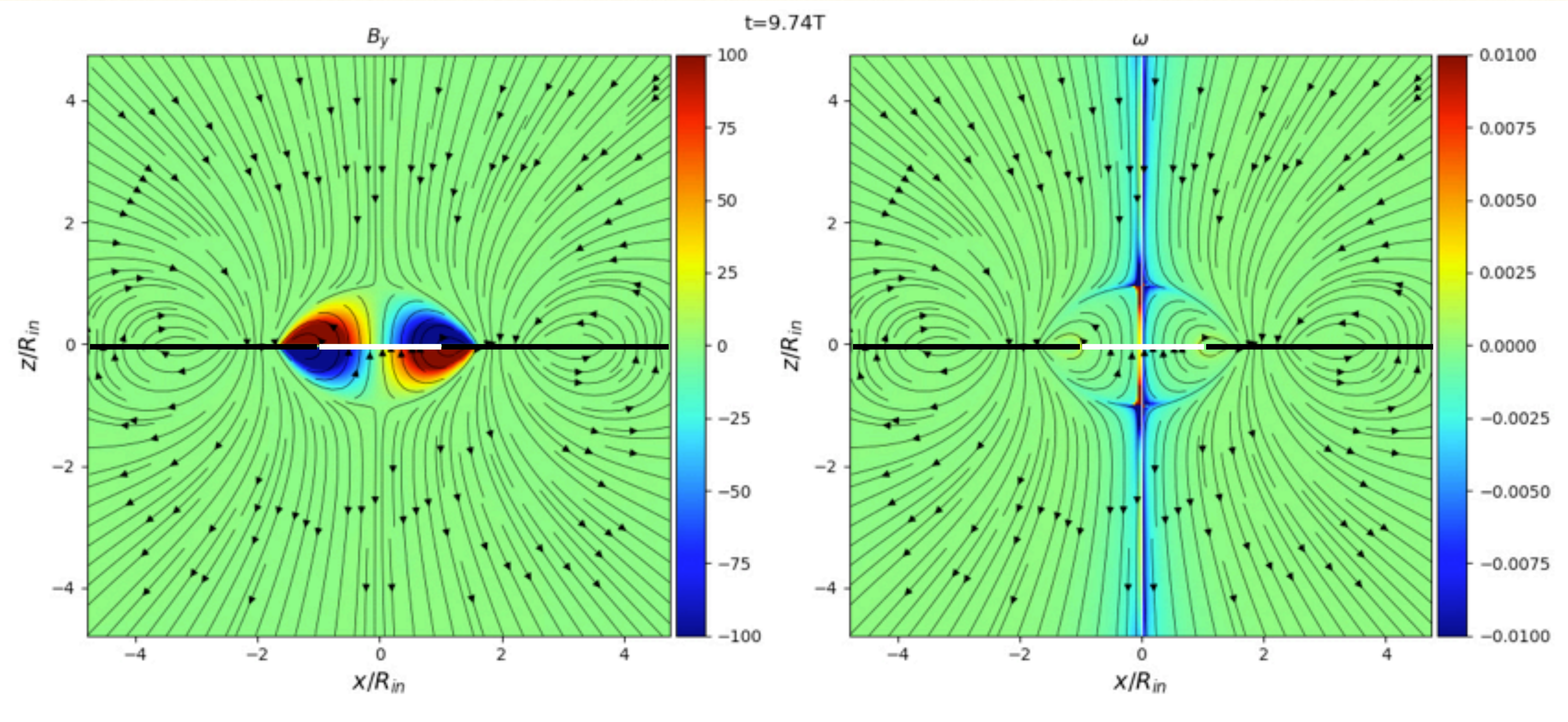


Kerr



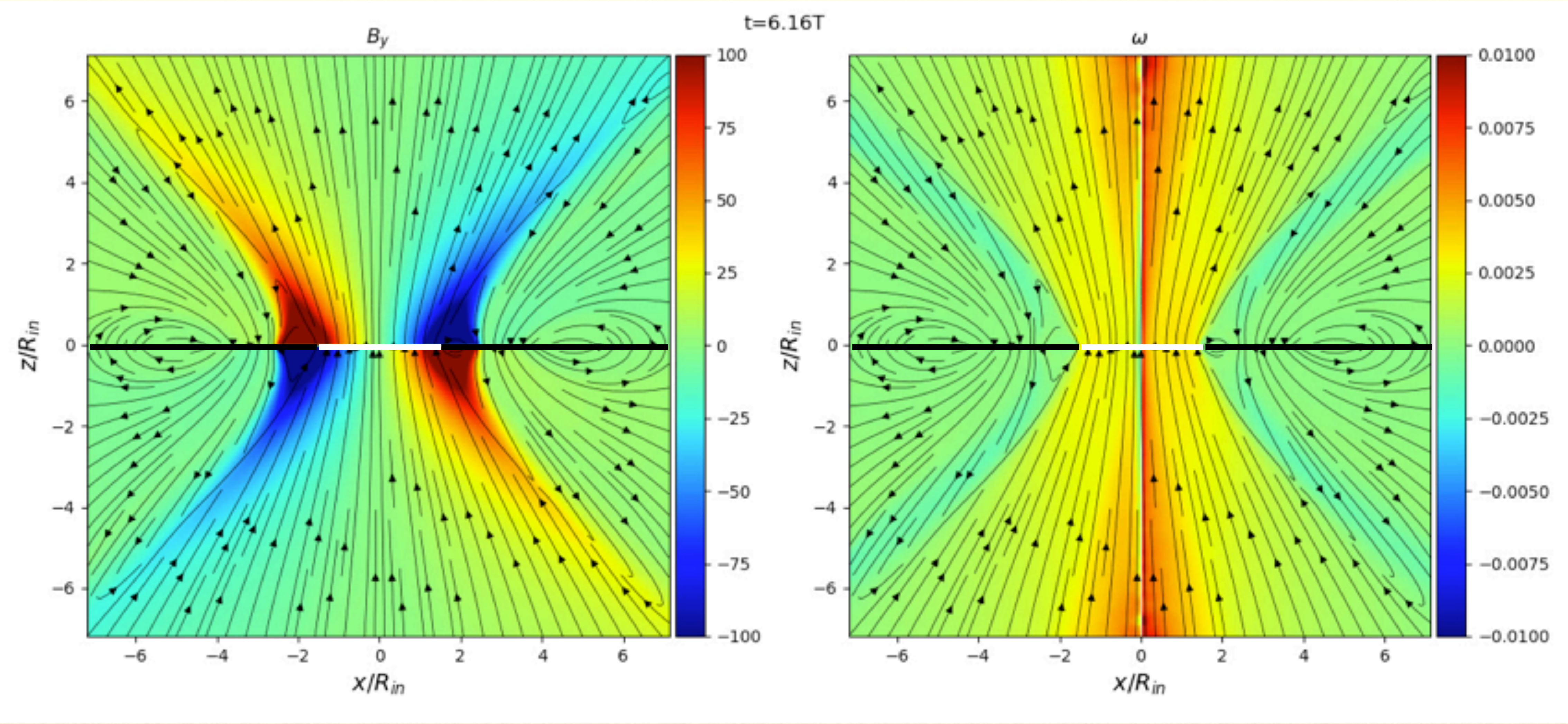
A test case

- A rotating resistive membrane disk (“BH”) surrounded by a perfectly conducting, non-rotating disk (“accretion disk”)
- Confined situation



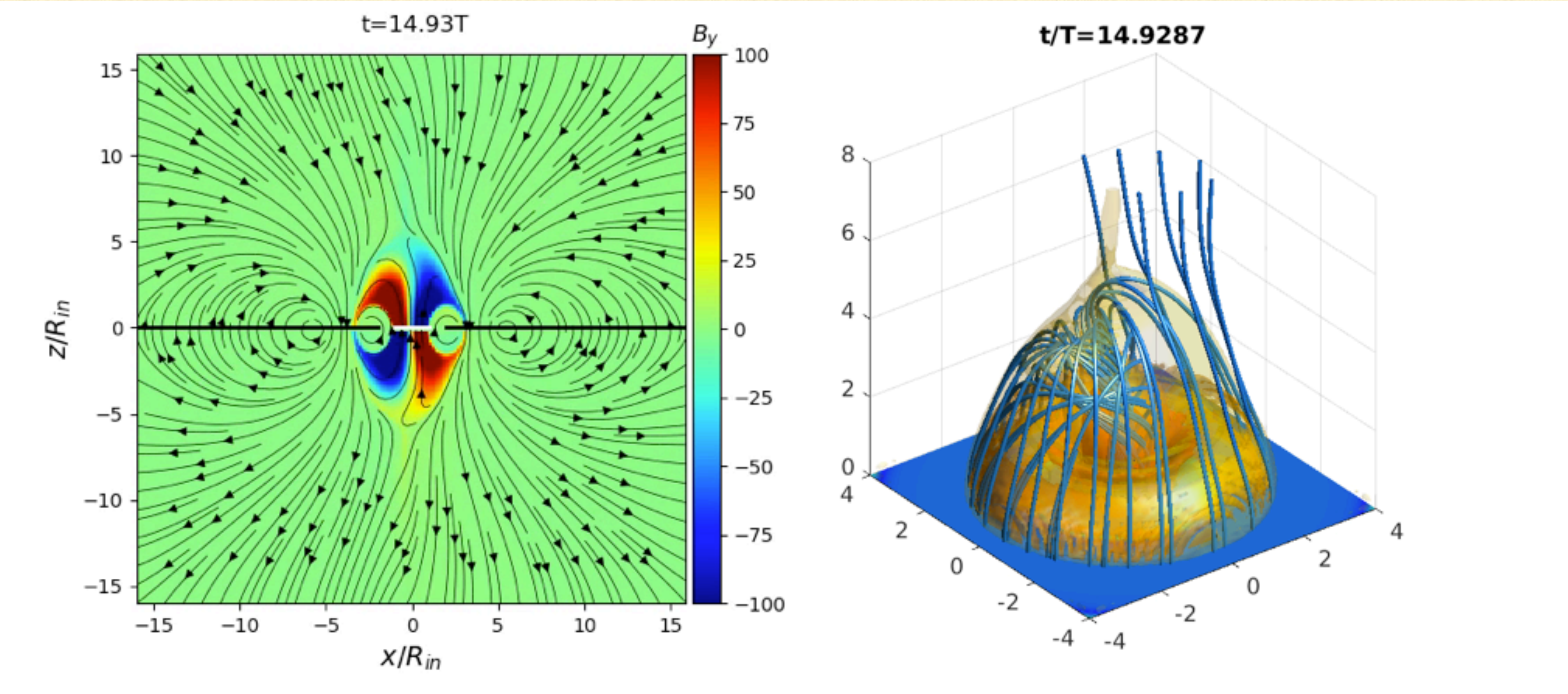
A test case

- Unconfined situation

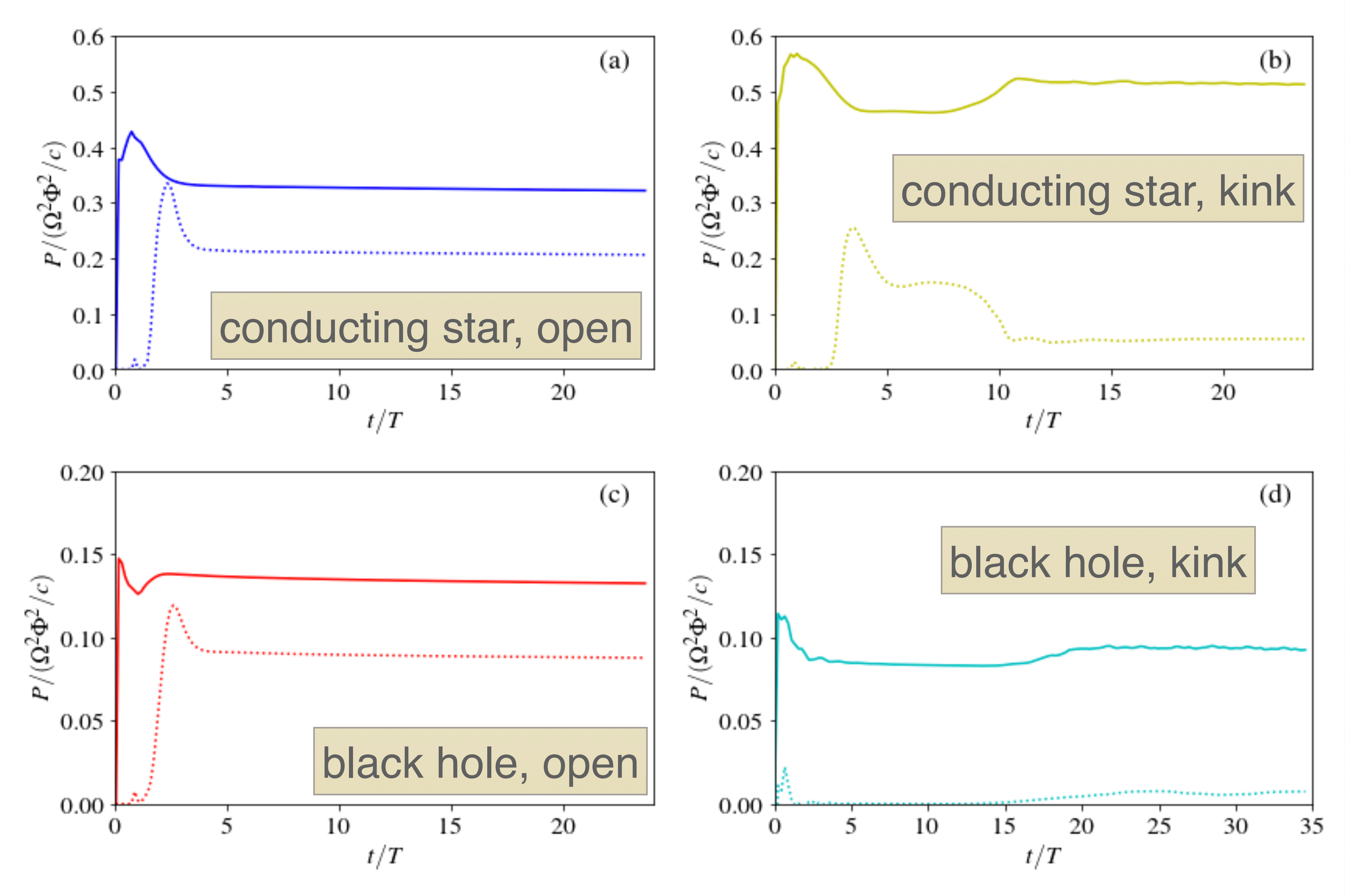


A test case

- Transitional regime: m=1 instability

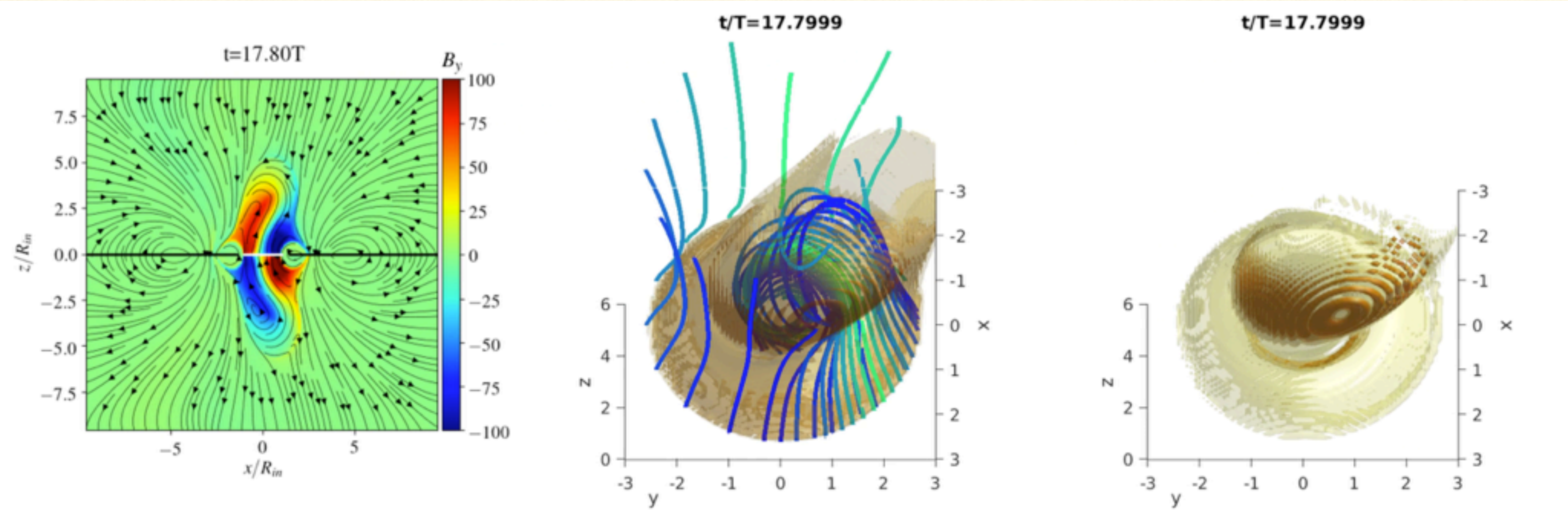


Poynting flux



Yuan et al, arXiv1901.02834

Simulation with resistive electrodynamics formalism & radiation signatures



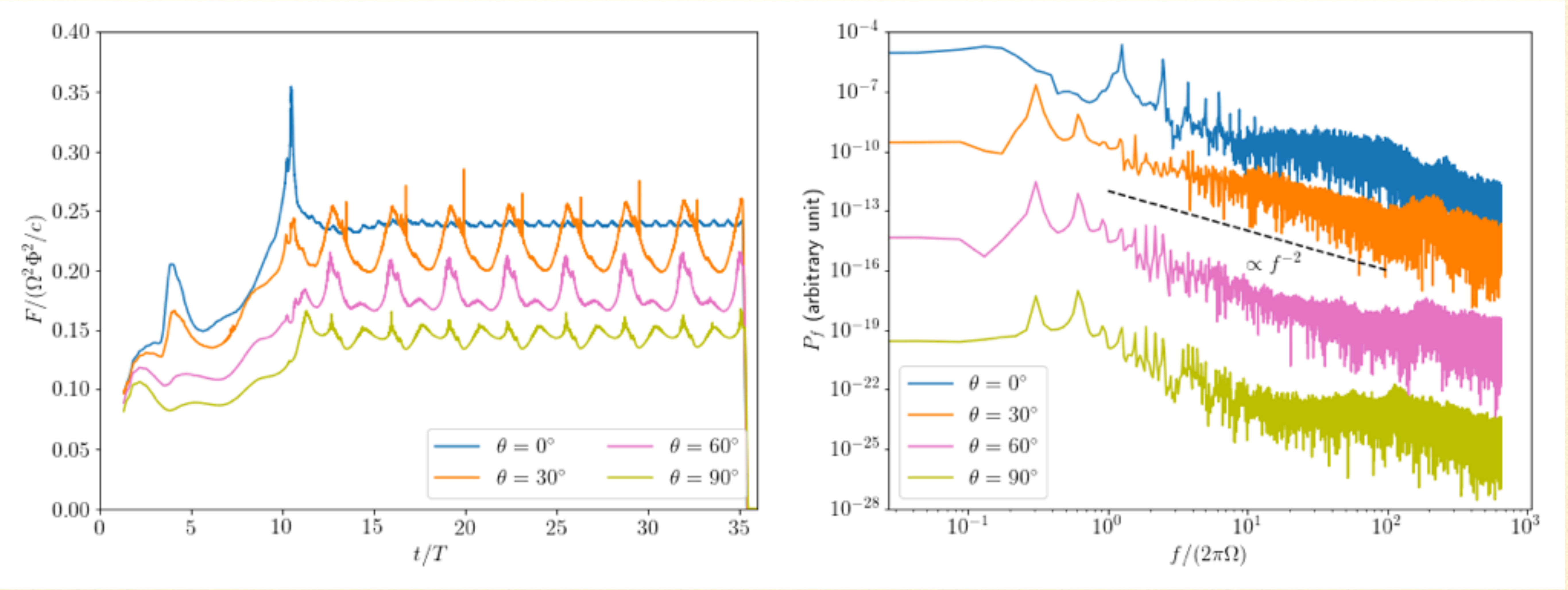
Field on x-z plane

3D field lines & current density

Emissivity

Formalism following Li, Spitkovsky & Tchekhovskoy 2012

Light curves and power spectra



Summary and Perspectives

- Compact, Lamppost-like coronae seem typical from observations
- Possible dissipation mechanisms:
  - Reconnection due to tangled small scale flux tubes near the axis may be a viable mechanism
  - This can be tested using GR force-free simulations, and maybe MHD simulations in the future.
- Next steps: understanding the microphysics of dissipation and particle acceleration using kinetic simulations